Journal of Hydrology: Regional Studies 4 (2015) 280–293

Contents lists available at ScienceDirect

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Implications of climate change on hydrological extremes in the Blue Nile basin: A review

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ARTICLE INFO

Article history:
Received 4 May 2015
Received in revised form 26 June 2015
Accepted 1 July 2015

Keywords:
Hydrological extremes
Climate change
Blue Nile River basin

ABSTRACT

Study region: The Blue Nile river basin in East Africa.
Study focus: This review paper presents the current understanding of hydrological extremes in the Blue Nile River basin under historic and future climate conditions, largely drawing on research outputs over the past decade. Characteristics of precipitation and streamflow extremes, including historic trends and future projections, are considered.
New hydrological insights: The review illustrates some discrepancy among research outputs. For the historical context, this is partially related to the period and length of data analyzed and the failure to consider the influence of multi-decadal oscillations. Consequently, we show that annual cycle of Blue Nile flow has not changed in the past five decades. For the future context, discrepancy is partially attributable to the various and differing climate and hydrological models included and the downscaling techniques applied. The need to prudently consider sources of uncertainty and potential causes of bias in historical trend and climate change impact research is highlighted.

Contents

1. Introduction

Increasingly frequent and intense hydro-climatic extremes in recent decades are accelerating impacts on natural and human systems (IPCC, 2012). The first decade of the 21st century has seen an unprecedented number of extreme events in different regions of the world; for example, in the United States in 2011 alone there were 14 extreme events topping $1 billion in damages, including tornados, severe flooding, droughts, and fires (Coumou and Rahmstorf, 2012). Floods in

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http://dx.doi.org/10.1016/j.ejrh.2015.07.001

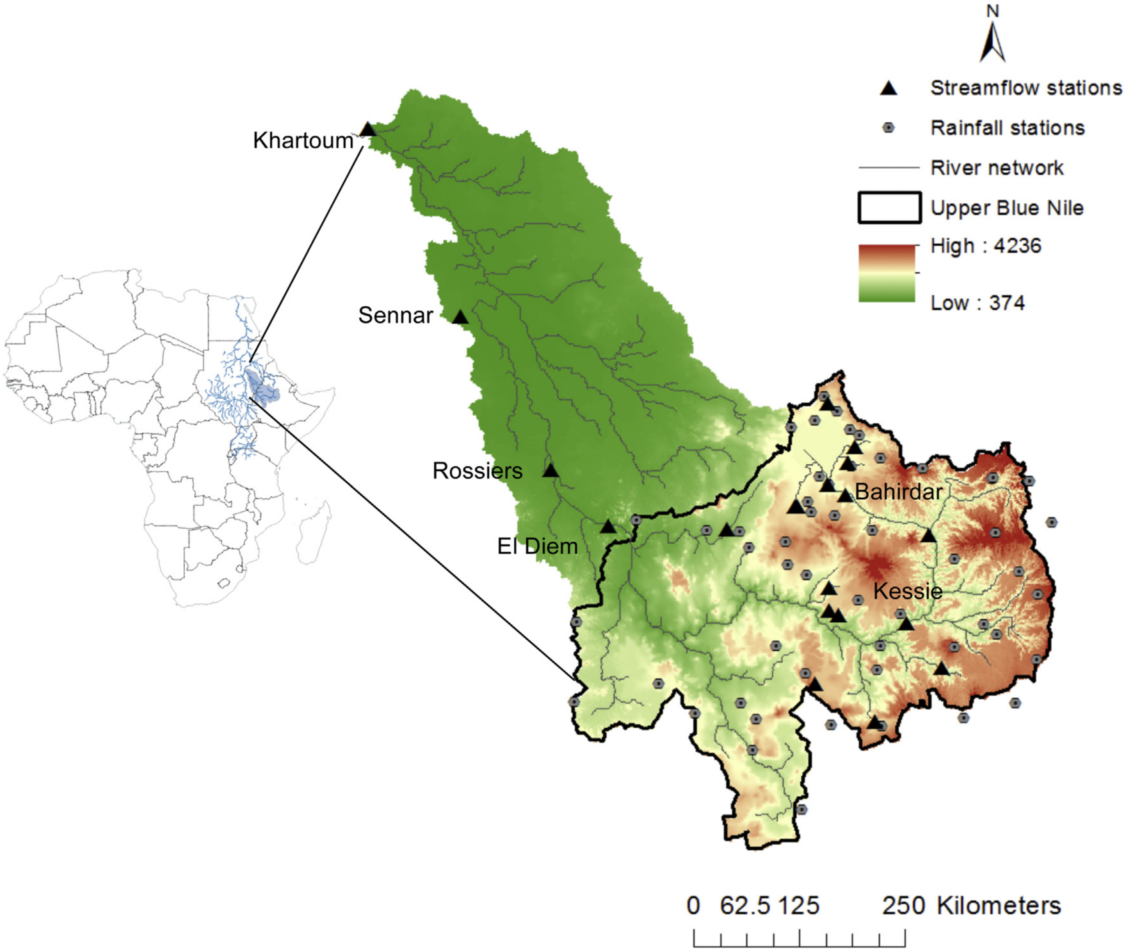

Fig. 1. Location of the Blue Nile basin in Africa and gauging stations used in the reviewed studies.

European rivers between 1998 and 2002 are responsible for the displacement of one-half a million people, 700 deaths, and in excess of 25 billion Euros in insured economic losses (Thielen et al., 2009). In response to such disastrous incidents, significant attention has been devoted to better understanding characteristics of hydrologic extremes and the potential association with non-stationary climate conditions. The Blue Nile River (BNR) basin in east Africa has been no exception, given its highly sensitive nature to precipitation variability at various time-scales and related hydrologic extremes.

The BNR basin is shared by Ethiopia and Sudan (Fig. 1) with an approximate drainage area of 312,000 km^2; the Ethiopian portion, the upper BNR basin, drains 176,000 km^2. The BNR exits Lake Tana in the Ethiopian highlands and travels 940 km to El Diem, near the Ethiopian Sudanese border, joined along the way by several important tributaries draining a large portion of western Ethiopia (Elshamy et al., 2009). In Sudan, the BNR receives water from two highly seasonal rivers, the Dinder and Rahad, and flows an additional 630 km to Khartoum, joining the White Nile (Awulachew et al., 2008). The upper BNR is the largest contributor to total Nile River flows, providing approximately 60% annually (Senay et al., 2014). Elevations in the basin vary from over 4000 m in the Ethiopian highlands to 350 m at the mouth (Awulachew et al., 2008).

Precipitation within the basin is highly seasonal, modulated primarily by the northward and southward migration of the Inter Tropical Convergence Zone (ITCZ), and to an extent, other large-scale oceanic-atmospheric drivers (Berhane et al., 2014; Block and Rajagopalan, 2007). Topography also influences precipitation patterns, although the relationship is not straightforward (Dinku et al., 2008). Annual precipitation rates in the highlands range from 800 to 2200 mm, with the majority falling during the June–September main rainy season known as "*Kiremt*", (Melesse et al., 2009). During this season erosion is considerable, contributing to loss of agricultural production in the Ethiopian highlands and excessive sediment in downstream countries (Betrie et al., 2011). The period October to May is usually a prolonged dry period with a short rainy season between March and May, known as "*Belg*". Climate change, specifically expected changes in the frequency and intensity of hydrological extremes (IPCC, 2012), is likely to exacerbate this, with implications across sectors, including subsistence rain-fed farming, large irrigation schemes, water supply, and hydropower generation, for both riparian countries.

In spite of the importance of the BNR to the entire Nile basin system, our knowledge regarding how large-scale climate patterns affect hydrologic extremes is not overly extensive. The El Nino-Southern Oscillation (ENSO) climate phenomenon, expressed through anomalous sea surface temperatures in the equatorial Pacific Ocean, has been shown to influence inter-annual variability of precipitation and streamflow (e.g., Block and Rajagopalan, 2007). Zaroug et al. (2014) demonstrate that when an El Niño event is followed by a La Niña event in the same year, there is a 67% chance of an extreme flood occurring in the BNR region. In contrast, it was found that 83% of El Niño events starting in April–June cause droughts in the upper BNR basin in Ethiopia. Temporal variability of precipitation and streamflow extremes have also been linked with low frequency climate processes centered over the mid-latitude Pacific basin (the Pacific Decadal Oscillation: PDO) and over the North Atlantic Ocean (the Atlantic Multi-decadal Oscillation: AMO) based on sea surface temperature anomalies (Taye and Willems, 2012).

This review paper presents the current understanding of hydrological extremes in the BNR basin under historic and future climate conditions. Consistencies and discrepancies across research studies addressing extremes are examined.

2. Characteristics and distributions of precipitation and streamflow extremes

Extreme hydro-climate events, often resulting in floods or droughts at local to basin-wide scales, are not uncommon in the region. Well-known examples include the devastating drought in the early 1980s in most parts of the Ethiopian highlands and the severe floods during August–September 1988 in Sudan (Sutcliffe et al., 1989). These events are directly related to precipitation extremes: a long period of well-below normal precipitation in the highlands and intense precipitation events over Khartoum and Atbara, respectively (Sutcliffe et al., 1989; Seleshi and Camberlin, 2005).

Daily precipitation extremes in the basin have not been explored extensively as many station records report predominantly at larger temporal scales. In one of the few studies available, Seleshi and Camberlin (2005) find that *Kiremt* season extreme precipitation in Ethiopia, defined as above the 95th percentile, is higher over the Ethiopian highlands and the western part of Ethiopia, where the BNR basin is located, than the eastern part of the country. Shang et al. (2011) report that large precipitation events in the Ethiopian highlands tend to occur in clusters; if the time-series is declustered and deseasonalized, the extremes can be explained by the Generalized Extreme Value distribution (GEV).

Streamflow extremes in the basin have been examined more intensively, using a variety of statistical methods common in water resources research. These include characterizing streamflows by fitting probability distributions and extreme value analysis, flood and low flow frequency analysis, analyzing long-term patterns at different temporal and spatial scales, and investigating explanatory variables describing streamflow variability. How extremes are defined is often study-specific, however common definitions include annual maximum/minimum streamflows, peak over threshold (POT) extremes, and streamflow thresholds exceeded a given percentage of time. Generally, for the BNR basin, high streamflows are concentrated between July and October, lagging the start of the *Kiremt* season by one month, while low streamflows occur between February and April. Melesse et al. (2009) observe greater in magnitude and more sustained streamflows along the main stem of the BNR at Kessie and Bahirdar stations than in the tributary rivers, which is not unexpected given the aggregation of streamflows across sub basins of varying characteristics and rainfall-runoff properties. Similarly, based on twelve sub-basins in the BNR basin, Gebrehiwot et al. (2014) illustrate the stark differences when comparing mean annual high streamflows, ranging from 525 mm/year to 26 mm/year, expressed as equivalent depth of water over the Beresa and Muger sub-basins, respectively. The mean annual low streamflows are on the order of less than 10 mm/year contributing as little as 0.1 to 3% of long-term mean annual streamflow.

Another set of studies examines streamflow characteristics by fitting probability distributions at various locations along the main stem of the river and its tributary rivers. Based on annual maximum streamflow at three Sudanese stations (El Diem, Sennar and Kharthoum), Abdo et al. (2006) demonstrate that each can be best fit with the three-parameter log normal distribution. In contrast, when stations located in the Ethiopian part of the BNR basin are analyzed, the probability distribution best explaining high and low streamflows varies by river. Melesse et al. (2009) examine two stations on the main stem (Kessie and Bahirdar) and five stations on the major tributaries (Gilgel Abay, Chemoga, Megech, Gumera and Ribb) of the basin. Their results suggest that high and low streamflows are best fit with diverse distributions, namely the General Pareto, Fréchet, Log normal, Log logistics, and Weibull distributions. This difference between stations is strongly related to location in the river network.

To fit the most extreme streamflows, explicitly a subset of the high streamflow time series that describes the tail behavior, a specific frequency distribution is applicable. Abdo et al. (2006) analyze the annual maximum streamflows of the El Diem, Sennar, and Kharthoum stations through extreme value analysis and visual inspection using quantile–quantile (Q–Q) plots. The result reveals a normal tail (extreme value distribution type I) for all the stations and the Gumbel distribution as the best fit to the annual maximum streamflows. The selection of GEV as the best distribution for peak streamflows is consistent with previous studies in the entire Nile river basin by Nyeko-Ogiramoi et al. (2012). Similarly, using extreme value analysis and Q–Q plots, Taye and Willems (2011) examine daily scale high and low streamflows at El Diem and four stations within the Ethiopian part of the basin. Daily extremes are estimated considering POT streamflows for different aggregation levels and return periods, in order to construct and calibrate flow-duration-frequency (QDF) curves; Exponential and Fréchet distributions are identified as best fits for high and low streamflows at all stations, respectively. Thus, the same type of extreme value distribution explains the tail behavior of streamflow extremes at various stations within this basin.

Spatial differences in characteristics of extremes are dependent on size, topography, land use, and other factors across Ethiopia (Melesse et al., 2009). For five stations on the BNR within Sudan, Willems et al. (2010) show that for each site, empirical annual maximum flood frequency curves rescaled by their mean mirror the established regional curve for high (non-flood) streamflow values. However, for high (flood) streamflows, topography and land use characteristics within the sub-basin, including embankment levels and the locations of low-lying floodplain areas, become increasingly influential. Gebrehiwot et al. (2011) also note spatial differences in low streamflow extremes, considering thirty-two sub-basins in Ethiopia across the period 1959–1963, with low streamflows in the western sub-basins substantially higher than in the eastern sub-basins.

3. Historical precipitation and streamflow trends

Investigating the existence of trends is a widely recognized statistical approach to detect non-stationarity in time series. Numerous studies regarding historical trends in precipitation and streamflow have been conducted in the BNR basin (Tables 1 and 2), with most studies focusing on annual and seasonal total precipitation and streamflow. Studies that explicitly considered extreme conditions are limited.

Considering precipitation trends, although varied outcomes at seasonal timescales across different parts of the basin exist, most studies report no significant trend in annual and seasonal precipitation totals (e.g., Conway, 2000; Seleshi and Zanke, 2004; Cheung et al., 2008; Tesemma et al., 2010; Gebremicael et al., 2013; Tekleab et al., 2013; Mengistu et al., 2014). Similarly, there is no statistical evidence for a conclusive decreasing or increasing trend in precipitation extremes (Seleshi and Camberlin, 2006; Shang et al., 2011) as well as in the severity and frequency of meteorological droughts in the basin (Bayissa et al., 2015).

At the BNR basin scale, no significant long-term trends exist for mean streamflows at the annual and seasonal scales (Conway, 2000; Awulachew et al., 2008; Melesse et al., 2009). Tesemma et al. (2010), however, report significant increases in discharge during the *Kiremt* season at three stations, Bahirdar, Kessie and El Diem, all situated on the main BNR. Dry season (October to February) streamflows show no significant trend at Bahirdar and Kessie but a significant decreasing trend at El Diem (10%). A significant increasing trend during the *Belg* season at Bahirdar (33%) and Kessie (51%) is noted, yet no change at El Diem. Similarly, Gebremicael et al. (2013) find statistically significant increasing trends of annual and *Kiremt* season streamflows, while dry season streamflows show a significant decreasing trend at El Diem. This indicates trends towards more severe hydrological extremes, in both high and low streamflow directions.

At the sub-basin scale, decreasing low streamflow trends are observed in parts of the basin. For instance, Rientjes et al. (2011) report that low streamflows in the Gilgel Abay sub-basin decreased during the past 30 years (1973–2001), specifically an 18.1% and 66.6% decrease for the periods 1982–2000 and 2001–2005, respectively. However, for the same periods, the high streamflows show an increase of 7.6% and 46.6%. Similarly for the Chemoga sub-basin, Bewket and Sterk (2005) observe a statistically significant decline of dry season streamflows (October–May) by 0.6 mm/year and a 94% decrease for February total streamflow during 1960–1999, while high streamflows do not indicate any discernable trend. These decreasing trends are explained by significant land cover changes in the basins observed during 1957–1998, specifically destruction of natural vegetative cover, expansion of cropland, overgrazing, and increased area under eucalypt plantations, spurring increased transpiration and declines in base flow. Comparatively, even though forest cover decreased significantly in the Koga sub-basin, no significant changes in runoff are reported for 1960–2002 (Gebrehiwot et al., 2010). This association with land use change is inferred after examining satellite (Landsat) images of two or three periods separated by a couple of decades. Another study by Tekleab et al. (2013) investigates nine streamflow gauging stations and finds trends in opposing directions. For streamflows in January, statistically significant decreasing trends are observed for Gilgel Abay and Jedeb stations (0.11 m^3/s/year and 0.015 m^3/s/year) while Koga and Gumera stations show statistically significant increasing trends (0.02 m^3/s/year). Low streamflow extremes, defined as 1- and 7-day annual minimum streamflows, show a significant decreasing trend in Gilgel Abay (0.05 m^3/s/year) and Muger sub-basins, however the 1-day annual minimum and maximum streamflow in Guder show a significant increasing trend (0.01 m^3/s/year). Finally, the 1-and 7-day annual maximum streamflows in the Neshi catchment display significant increasing trends. Comparably, dry season (October–February) streamflows show decreasing trends at the Muger and Jedeb stations. No discernable significant trends were observed for the Ribb and Chemoga sub-basins. Gebrehiwot et al. (2014), however, find decreasing high streamflow trends for the Birr and Guder sub-basins and decreasing low streamflow trends for Gilgel Abay and Muger, where high and low streamflows are defined as total average streamflow across the wettest and driest month, respectively.

Although there are some contradictory findings across these studies, generally speaking, it appears there are no statistically significant precipitation trends in the Ethiopian highlands, yet statistically significant streamflow trends are evident in some of the tributary catchments. Thus, while basin-scale hydrology has been relatively stationary for the last half of 20th century, trends in sub-basins do exist, with adjacent sub-basins not necessarily changing in similar directions (Gebrehiwot et al., 2014). Figs. 2 and 3 summarize the findings for high and low streamflow trends in the ten sub-basins discussed above. Low streamflows are shown to have significant decreasing or increasing trends in 11 out of 18 cases, or 61%. Comparatively, no significant change is evident for high streamflows in 13 out of 18 cases (72%). This illustrates that low streamflows in the basin are historically more sensitive to change than high streamflows. However, for four sub-basins, results for low streamflow trend direction are inconsistent (Fig. 2). Temporal variability of extreme quantiles in the BNR basin scale illustrates a multi-decadal pattern, suggesting that trend studies based on short-term data can be misleading (Taye and Willems, 2012). Accordingly, reported increasing trends of BNR flows during the *Kiremt* season (e.g. Gebremicael et al., 2013) may not be significant if only data prior to the 1970s is included in the analysis.

Table 1
Overview of selected research findings on historical trends in precipitation totals and extremes in the Blue Nile basin.

Data length	Variable and season (s)	Results	References
1965–2002	Extreme precipitation intensity in the *Kiremt* season	Decreasing trends are observed in eastern, southwestern and southern parts of Ethiopia The other part of the country has no trend	Seleshi and Camberlin (2006)
1953–2006	Extreme precipitation	No significant trend is found for stations located in the northwestern highlands of Ethiopia	Shang et al. (2011)
1978–2007	Precipitation greater than 20 mm/day in the *Kiremt* season	In the central highlands of Ethiopia high precipitation variability, more extreme precipitation during the start of the main rainy season and more number of rainy days during the same season is found	Rosell (2011)
1900–1998	Total precipitation on annual basis	No long-term trend is found in the northeastern Ethiopian highlands	Conway (2000)
1965–2002	Total precipitation in *Kiremt* season and annual	No trend in precipitation totals or number of rainy days over central, northern and northwestern Ethiopia A decline is detected in eastern, southwestern and southern parts of Ethiopia	Seleshi and Zanke (2004)
1961/73–2003	Daily precipitation	No consistent patterns or trends in daily precipitation characteristics are observed in Amhara region in Ethiopia	Bewket and Conway (2007)
1960–2002	Total precipitation in *Kiremt* season and annual scale	No significant changes in annual precipitation are reported for the 13 watersheds examined in Ethiopia However, a significant decline (by 7.0 mm/year) in *Kiremt* precipitation is found for watersheds located in the southwestern and central parts of Ethiopia in which the Southern BNR is part of it	Cheung et al. (2008)
1963–2003	Total precipitation in *Kiremt* season	No significant trend in the seasonal and annual basin-wide average precipitation in the upper BNR basin	Tesemma et al. (2010)
1972–2011	Total precipitation in *Belg* and *Kiremt* seasons	Precipitation decline in southern Ethiopia is found during both seasons while central and northern Ethiopia did not display similar tendencies However, frequency of *Belg* droughts increased in all parts of Ethiopia during the last 10–15 years of the study period	Viste et al. (2012)
1970–2009	Total precipitation in annual basis	No significant change in annual precipitation in eight out of nine stations in the upper BNR basin	Gebremicael et al. (2013)
1970–2010	Total precipitation in *Kiremt* season, monthly and annual scale	No statistically significant trends in mean annual and seasonal scales across 13 stations with in he upper BNR basin	Tekleab et al. (2013)
1981–2010	Total precipitation at seasonal and annual scale	Statistically non-significant increasing trends at annual timescale (5 mm/decade) and all seasons except *Belg* season A statistically non-significant declining trend during spring season in the northeastern part of the upper BNR basin	Mengistu et al. (2014)
1954–2004	Total precipitation in *Belg* and *Kiremt* seasons and annual scale	Significant decreasing trend only at two locations with rate of −2.30 and −9.25 mm/year for *Kiremt* season	Tabari et al. (2015)
1953–2009	Total precipitation in February–April, July–September seasons and at annual scale	No conclusive evidence in increasing or decreasing meteorological drought based on SPI drought index in the upper BNR basin	Bayissa et al. (2015)
1948–2006	Total precipitation on annual basis	Decreasing trends (−0.4 mm/month/year) over Ethiopia's southwestern region	Jury and Funk (2013)

Table 2
Overview of selected historical trend studies of mean, high and low streamflows in the Blue Nile basin.

Data length	Variables	Basin (sub-basin)	Results	References
1973–2001	Low and high streamflows	Gilgel Abay	Low streamflow index (Q_{95}/Q_{50}) decreased by 18.1% and 66.6% for the periods 1982–2000 and 2001–2005 respectively High streamflow index (Q_5/Q_{50}) increased by 7.6% and 46.6% for the same periods	Rientjes et al. (2011)
1957–1998	Low and high streamflows	Chemoga	Decline at monthly and daily scales a statistically significant decline by 0.6 mm/year for dry season streamflow (October–May) and a 94% decrease at monthly scale for February streamflow No discernible trend of monthly and daily high streamflows	Bewket and Sterk (2005)
1960–2002	Low and high streamflows	Koga	No change in the hydrology of sub-basin in spite of land use change	Gebrehiwot et al. (2010)
1963–2003	Mean seasonal streamflow	Upper BNR	Significant increases in discharge during *Kiremt* season at Bahirdar, Kessie, and El diem (26%, 27% and 10%) No significant trends at Bahirdar and Kessie but a significant decreasing trend (10%) at El Diem for the dry season A significant increasing trend at Bahirdar and Kessie (33% and 51%) while no change at El Diem during *Belg* season	Tesemma et al. (2010)
1970–2009	Mean seasonal and annual streamflow	Upper BNR	Statistically significant increasing trends of annual and *Kiremt* season streamflow Significant decreasing trend in the dry season flow	Gebremicael et al. (2013)
1970–2010	Mean annual, rainy season, dry season and small rainy season streamflow. Extreme streamflows given as 1-day annual maxima/minima and 7-day annual maxima/minima	Upper BNR	No discernable significant trends in hydrological variables are observed for Ribb and Chemoga sub-basins Significant decreasing trends for monthly streamflows during dry season (December–February) for Jedeb sub-basin ($-0.015\ m^3/s/year$)	Tekleab et al. (2013)
1960–2004	Annual total, high, low streamflow, runoff coefficient and low streamflow index	Upper BNR	Generally, no significant change in twelve sub-basins for all variables. The exceptions are: Significant decreasing trend of Gilgel Abay low streamflows and low streamflow index Significant increasing trend of Andasa and Koga runoff coefficient Significant deceasing trend of Guder annual total streamflow	Gebrehiwot et al. (2014)

An analysis of daily data from 1964 to 2009 at the El Diem station reveals that the annual cycle of Blue Nile flow has not changed in the past five decades (Fig. 4a). Likewise, annual daily maximum streamflow does not indicate any trend (Fig. 4b) supporting the argument that the basin has been stable for the considered period. However, if data starting from the 1970s is considered, increasing trend can be observed (Fig. 4c) supporting our contention that different periods can lead to different conclusion on trend analysis. Therefore, multi-decadal (low-frequency) patterns are clearly evident on high flows, as demonstrated by Taye and Willems (2012). The annual daily minimum streamflow shows an increasing trend after late 1990s (Fig. 4d). This coincides with the construction of the Chara–Chara weir at the outlet of Lake Tana that facilitates storing water during the wet season and releasing during the dry season to generate electricity (Tesemma et al., 2010; Taye and Willems, 2012). The sensitive nature of dry period streamflow for changes in land and water management activities can be observed from this analysis.

4. Future projections on hydrological extremes

General Circulation Models (GCMs) are the primary tools developed for the investigation of climate change. These models provide information on the response of the climate system to an increase in greenhouse gases by projecting various hydro-climatic variables to a future period. GCMs are typically run at horizontal resolutions in the range 250–600 km (IPCC, 2012), a scale often too course for local impact assessment. Hence, statistical or dynamical downscaling is frequently employed to bridge the spatial disparity between global and local scale. Higher resolution dynamical Regional Climate Models (RCMs) may be nested within GCMs for better representation of local features such as topography and land cover. RCMs, however, require significant computing facilities and technical expertise, and therefore have not been applied globally. Other approaches

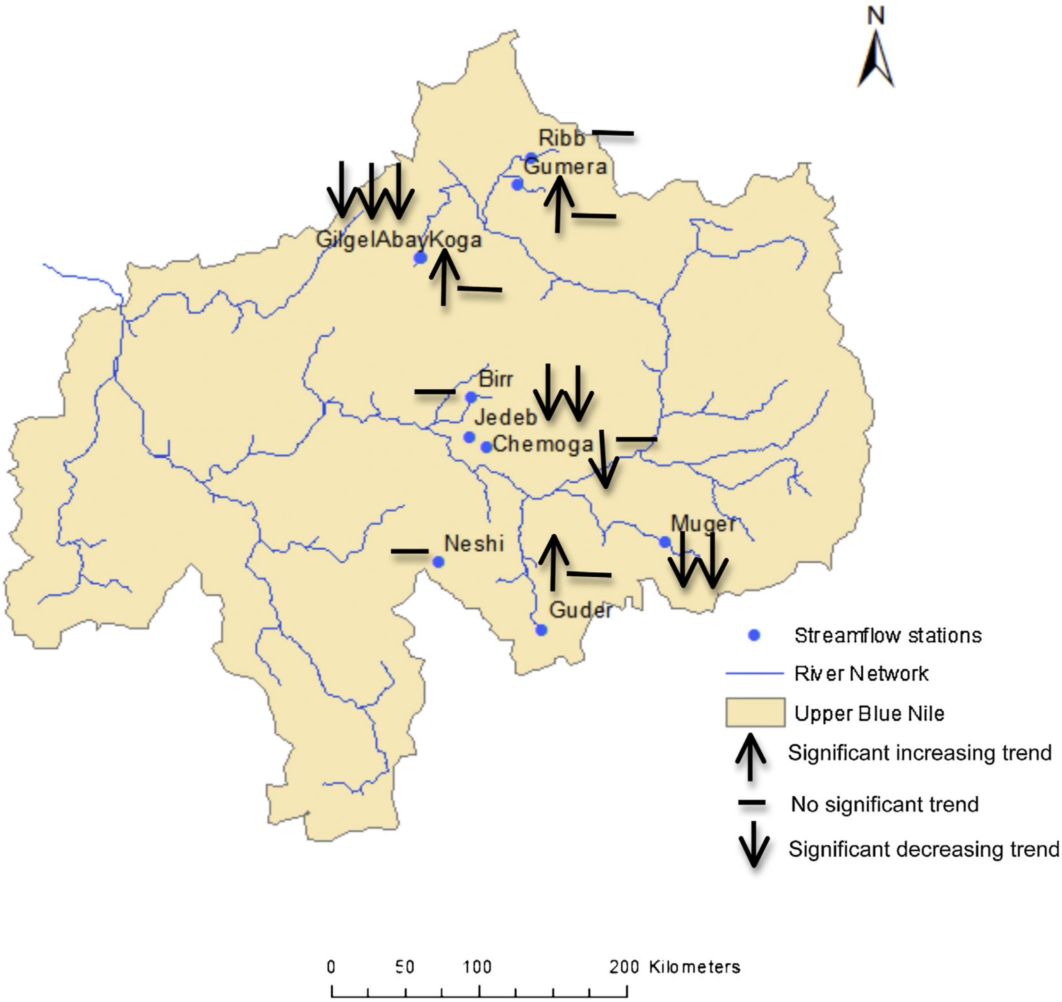

Fig. 2. Direction of historical low streamflow trends from selected sub-basins presented in this review. The number of arrows indicates the number of studies for each specific basin (e.g., three arrows represent three studies for Gilgel Abay).

include applying statistical methods and/or bias correction or climate change signal propagation. These approaches can be directly applied to GCMs or RCMs. GCMs do not simulate streamflow, thus projected hydro-meteorological time series must be applied to separate process models (e.g., rainfall-runoff or other impact assessment models) to obtain projected streamflow response.

In the BNR basin, climate change investigations typically address results at mean annual and seasonal scales by statistically downscaling and/or bias correcting GCM outputs with subsequent simulation in hydrologic models as needed. GCM outputs based on the Special Report on Emission Scenarios (SRES) have been used extensively. These scenarios are expressions of how the future might unfold from the interaction of dynamic systems encompassing economic, demographic, social, technological and environmental developments of the future world and related greenhouse gases emissions (Nakicíenovicí et al., 2000). These scenarios are named as A1T, A1B, A1FI, A2, B1, and B2 and are designated as equally valid, with no assigned probabilities of occurrence. For instance, A2 is at the upper side of the SRES emissions scenarios referring to a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines (Nakicíenovicí et al., 2000). In the BNR basin with some exceptions, most studies generally address two periods in the 21st century for climate change impact evaluation: mid-century (2050s) and end of century (2080s).

For these future horizons, expected changes in precipitation characteristics are unclear. Beyene et al. (2007) report a 24% increase in precipitation projection late in the 21st century (2070–2099) using 11 GCMs, while Elshamy et al. (2009) report almost no expected change in precipitation considering the ensemble mean of 17 GCMs. Generally there is no consensus among the GCMs on the direction and magnitude of precipitation change at basin-wide or sub-basin scale within the upper BNR basin (e.g., Setegn et al., 2011; Taye et al., 2011; Enyew et al., 2014). Conversely, most studies project a clear increase in temperature by the end of the 21st century, on the order of 2–5 °C (Elshamy et al., 2009; Beyene et al., 2007). Elshamy

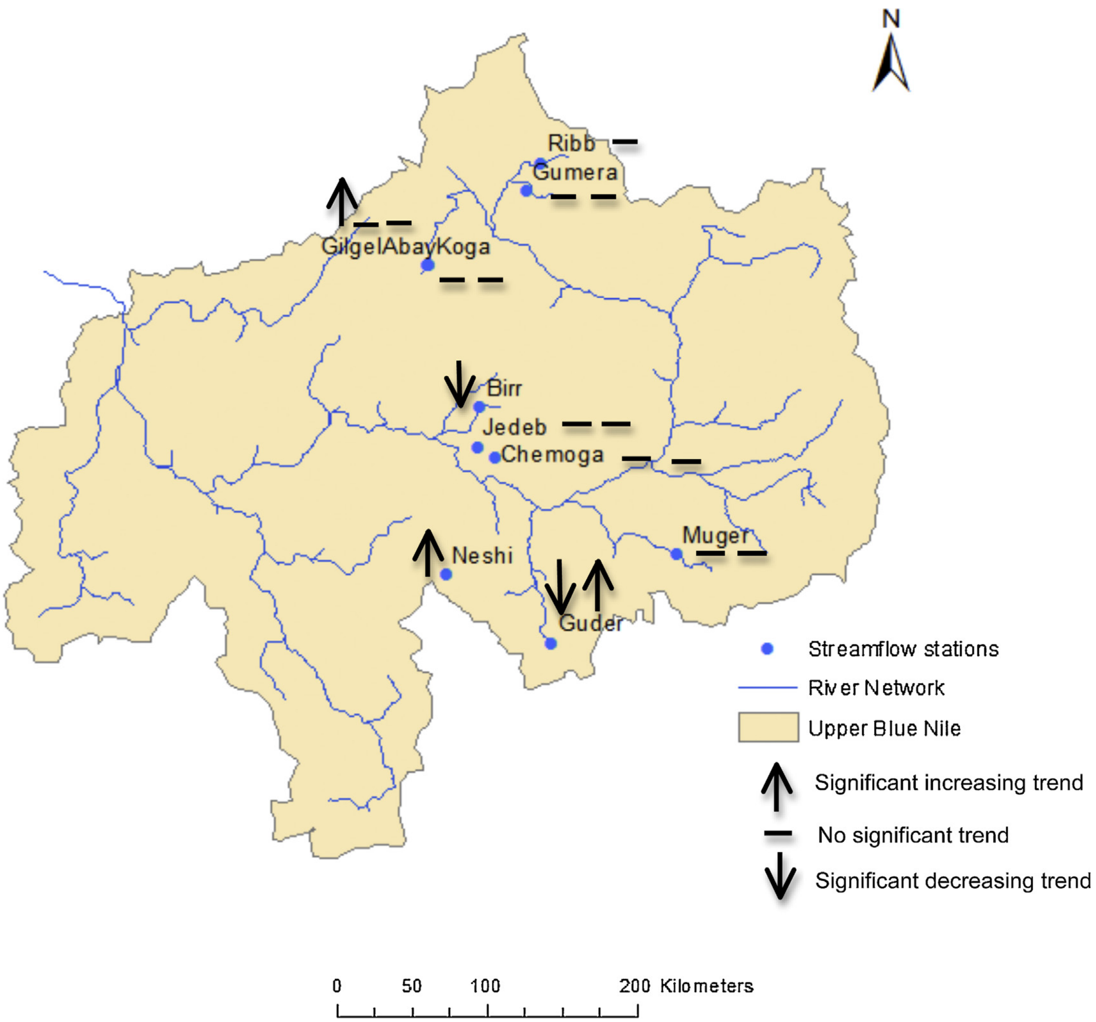

Fig. 3. Direction of historical high streamflow trends from selected sub-basins presented in this review. The number of arrows indicates the number of studies for each specific basin (e.g., two arrows represent two studies for Guder).

et al. (2009) report expected increases in potential evapotranspiration (2–14%) by 2080s, driven predominantly by projected increases in temperature. Consequently, they conclude that assuming no change or moderate change in precipitation and increasing potential evapotranspiration, the upper BNR basin might become more moisture constrained in the future.

Regarding streamflow, Beyene et al. (2007) report a projected increase in streamflow of 26% for 2010–2039 and a decrease of −10% for 2070–2099 using A2 emissions scenario, highlighting the expected temperature gradient influence toward the end of the 21st century. Elshamy et al. (2009) also report reduced prediction of mean annual streamflow by 15% for the 2080s compared to the baseline period (1961–1990). Unlike the previous studies that used an ensemble mean approach based on GCM runs, Soliman et al. (2009) use the RegCM3 regional model outputs to assess streamflow projections for the period 2034–2055 under the A1B scenario. The results indicate that while changes in precipitation might vary spatially across the upper BNR basin, expected annual streamflow increases only slightly (1.5%); a larger increase (10%), however, is projected during the onset of the *Kiremt* season. The cessation of the *Kiremt* season and the dry season tend to favor a slight decrease in runoff.

The number of climate change studies investigating extreme streamflow conditions is limited (Table 3). A wide range of extreme streamflow projections is reported, attributable to the wide range of precipitation projections. At the upper BNR basin scale, in spite of these wide projections, an overall increase in high and low streamflows is expected, prompting a reduction in drought events for the 2050s and 2080s (Kim et al., 2008; Nawaz et al., 2010). For instance, Kim et al. (2008) use six GCMs to evaluate extreme streamflow statistics (Q_{10} and Q_{90}, streamflow exceeded 10% and 90% of the time representing high and low streamflows, respectively) for the 2050s at six sub-basins. They find a large range of expected changes in Q_{90} (−25% to 60%) and a smaller, but still sizeable range in Q_{10} (−15% to 20%). They argue that low streamflows dominate the period from February to May and these are highly controlled by the quantity and timing of precipitation from November to February of the previous year. Hence, a larger percentage change in Q_{90} compared with Q_{10} is related to streamflow

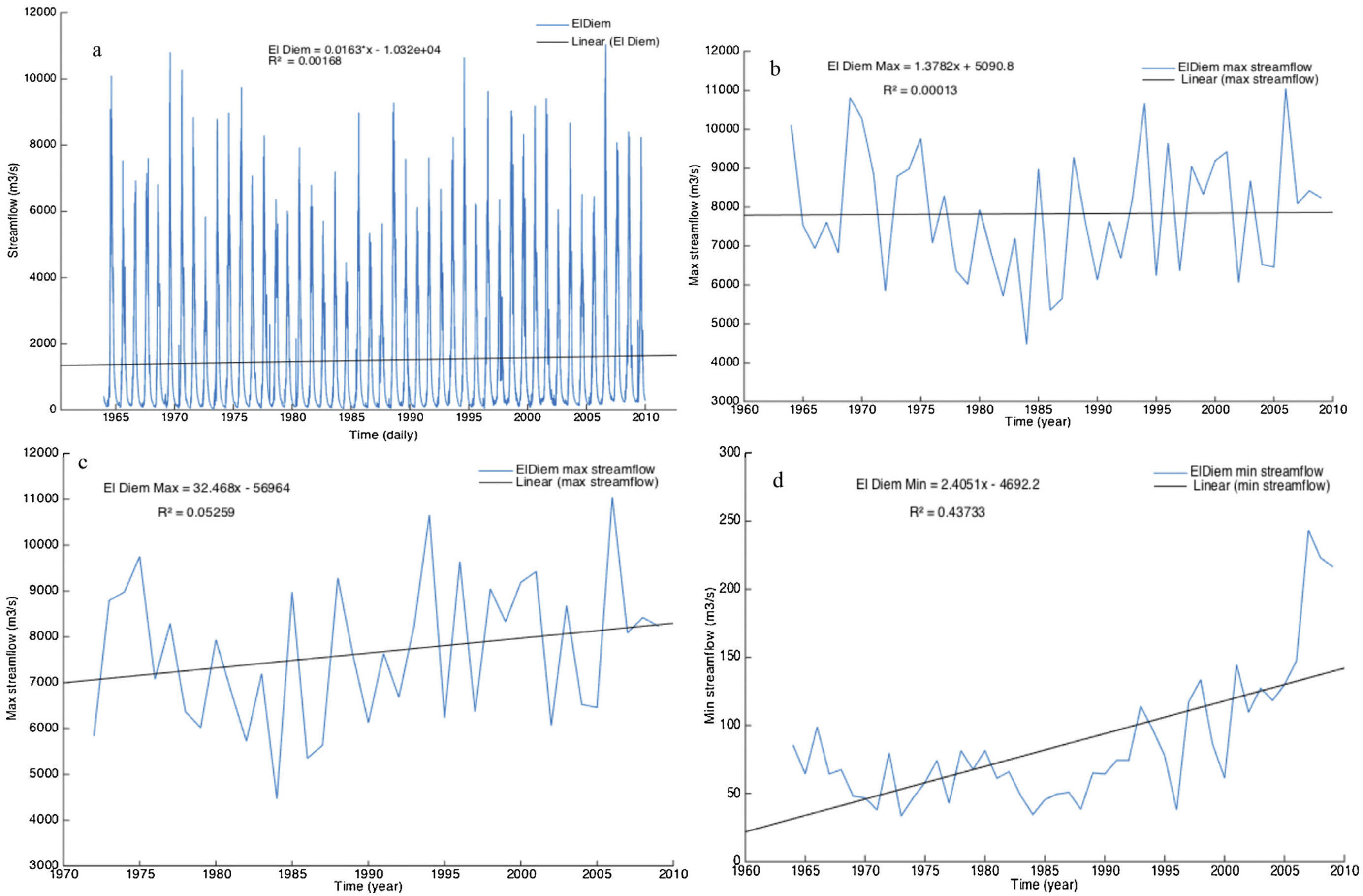

Fig. 4. El Diem streamflow for the period 1964-2009 for (a) daily data, (b) annual maximum, (d) annual minimum, and (c) annual maximum flow for the period 1972–2009. Linear trend lines are also included.

Table 3
Overview of selected future projections of high and low streamflows in the Blue Nile basin.

Climate projection	Hydrological variable	Basin (sub-basin)	Bias correction or downscaling method	Projection horizon and results	Reference
Six GCMs (A2)	Q_{90} Q_{10} Precipitation deficit of 6-months (SPI6)	Upper BNR divided into six sub-basins	Triangular cubic interpolation method	2050s Large increase in low streamflow statistic (Q_{90}) and wider range (−25% to 60%) Slight increase in high streamflow statistic (Q_{10}) and narrower range (−15% to 20%) Reduced severe drought events	Kim et al. (2008)
Three GCMs (A2, B2)	Q5 Q1	Upper BNR	Non-linear regression	2020s, 2050s, and 2080s Wide range of change for Q5 (−43% to +32%)	Nawaz et al. (2010)
Five GCMs (RCP2.6, RP8.5)	Q_{90} Q_{10}	Upper BNR	Trend-preserving bias correction	2050s and 2080s An increase in high flows (Q_{10}) from 10% to 50% An increase in low flows (Q_{90}) from 40% to 60%	Aich et al. (2014)
17 GCMs (A1B, B1)	Daily scale high and low streamflows for return periods between 1 and 10 years	Lake Tana sub-basin	Quantile pertubations	2050s Unclear projection consisting of both increasing and decreasing trends Based on average for all return periods, high streamflows change from −31% to +79% and low streamflows change from −61% to +56%	Taye et al. (2011)
Three GCMs (A2)	Q_{80}	Lake Tana sub-basin	Bias correction using the Water and Global Change (WATCH) Forcing Data	2040s and 2080s Results do not agree on the direction and magnitude of the drought characteristics	Enyew et al. (2014)
One GCM (A2, B2)	Q95 Q70	Gilgel Abay sub-basin	Multiple linear regression	2020s, 2050s, and 2080s No major effect for low flows of Q95 Decrease in Q70 during the 2020s and 2050s while increase in the 2080s	Dile et al. (2013)

magnitudes. Nevertheless, Q_{90} tends to favor a wetter dry season for the study area. On the other hand, increasing Q_{10} indicates that flood risks to downstream countries may increase compared with current climate conditions. Nawaz et al. (2010) also report the possibility of more severe floods in the future based on Q_5 and Q_1 streamflows during *Kiremt* season for three future periods (2020s, 2050s, and 2080s). For the Q_5 streamflows, the full range of likely change is projected to be between −43% and +32%. In spite of the wide range, the study concludes that future wetter conditions in the basin may result in increased extreme streamflows. Kim and Kaluarachchi (2009) argue that the projected increasing trend of precipitation over the BNR basin may reduce the frequency of severe drought events for the 2050s horizon.

The aforementioned studies mainly project increasing tendencies of hydrologic extremes using climate model runs from the 4th IPCC Assessment Report (AR4). Given the new generation of climate models produced for the 5th IPCC Assessment Report (AR5), Aich et al. (2014) consider two scenarios (Representative Concentration Pathways (RCP) 8.5 and RCP 2.6). RCPs are defined by selecting concentration pathways and the associated radiative forcing in 2100. Hence, RCP 8.5 indicates rising radiative forcing to 8.5 W/m^2, representing the largest emissions and RCP 2.6 indicates radiative forcing peaking at 2.6 W/m^2 before 2100 and decline, representing the lowest emissions. They conclude that the most extreme streamflows will likely increase in the upper BNR basin, ranging from 10% to 50% for Q_{10} and between 40% and 60% for Q_{90}. This is in slight contrast to Kim et al. (2008) who use the AR4 GCMs and find both positive and negative expected changes for Q_{90} and Q_{10} (Fig. 5).

Looking at sub-basin spatial scales, expected future streamflow changes in the Lake Tana sub-basin, which contains the headwaters of the BNR, are not uniform. At the annual scale, statistically significant declines in streamflow are reported by Setegn et al. (2011), while Kim et al. (2008) show an increasing trend in mean and extreme streamflows for the 2050 horizon. Using 17 GCMs with A1B and B1 scenarios for the same 2050s horizon, Taye et al. (2011) discover that changes in high streamflows vary from −31% to +79% and low streamflows vary from −61% to +56%. Similarly, using three GCMs, Enyew et al. (2014) report that projections of drought characteristics for future periods do not agree on the direction or magnitude for the Lake Tana sub-basin.

For the Gilgel Abay sub-basin, located in the Lake Tana region, using the HadCM3 (Hadley center Climate Model 3) GCM, Dile et al. (2013) illustrate an expected decrease in monthly streamflow on the order of −40% to −50% for the period 2010–2040 and a more than double increase for the period 2070–2100. This study also suggests negligible effects on low streamflow conditions along the river. In contrast, for the same sub-basin Abdo et al. (2009) show expected *Kiremt* season runoff decline by 11.6% and 10.1% for the A2 and B2 scenarios, respectively, by the 2080s.

5. Discussions

Changes in hydrology and water resources due to climate or land use/cover modification deserves concerted attention in the BNR given the massively dependent population on rain-fed agriculture. Several studies state that the upper BNR basin has been experiencing considerable change in land use/cover and sizable soil degradation over many decades (Gete and Hurni, 2001; Hurni et al., 2005; Zegeye et al., 2010; Asmamaw et al., 2011; Gebremicael et al., 2013; Tekleab et al., 2014). Most of these studies highlight the conversion of natural vegetation into agricultural cropland as the most common land use/cover change in the basin. Detecting the impact of this local change on basin-wide hydrology is non-trivial. Bloschl et al. (2007) argue that the impact of land cover change decreases with catchment size as such changes are typically a local phenomenon. As reported in numerous publications, trend changes at the basin-wide scale are minimal while sub-basin specific changes are evident in some sub-basins. This can result from a combination of diverse geology, complex topography, the amount of rainfall at different locations, and land and water management practices specific to the sub-basins, smoothing out the total effect on downstream BNR runoff. High spatial variation is detected in sub-basins runoff and extremes predominantly when controlled by land use and topography of the sub-basins (e.g., Gebrehiwot et al., 2011; Haregeweyn et al., 2015). Moreover, it is important to note that low streamflow appears to be more sensitive to changes in land and water management modifications in some sub-basins. Some of the contradictory results in the trend studies may be attributed to the period used for the analysis and omission of the multi-decadal oscillation aspect of the basin.

A study by Di Baldassarre et al. (2011) reviewing the expected effects of climate change on the water resources of the Nile river basin discusses the importance of accounting for climate change uncertainty on the future hydrology of the basin, and its necessity for effective decision-making and suitable adaptation strategies. Across the studies review here, it is evident that there is disagreement among GCMs in simulating future precipitation of the BNR basin at different spatial scales, however there appears to be more consistency in the direction of temperature projections. Chen et al. (2011) argue that major sources of uncertainty stem from GCMs and emission scenarios, yet uncertainty related to the choice of downscaling method or bias correction is often given less attention. Most studies in the BNR basin apply a single downscaling or bias correction technique in their analysis and thus fail to propagate the uncertainty in this process (e.g., Elshamy et al., 2009; Kim and Kaluarachchi, 2009; Beyene et al., 2010). Bias correction can produce large increases in precipitation that may lead to extreme streamflow conditions, even in excess of 100% in some cases (Aich et al., 2014). Ebrahim et al. (2013) compare three downscaling techniques: Statistical Downscaling Model (SDSM), the Long Ashton Research Station Weather Generator (LARS-WG) and an Artificial Neural Network (ANN), to evaluate hydrologic impacts of climate change in upper Beles sub-basin. Their research highlights precipitation and temperature sensitivity to downscaling techniques and demonstrates the need for tremendous caution in interpreting and using the output of a single downscaling technique. An ensemble approach considering a range of climate models, greenhouse scenarios, downscaling methods and even hydrologic models, is recommended.

The selection of a hydrologic modeling approach is another important component of climate change impact studies in water resources. Both conceptual and semi-distributed hydrologic models are used in the assessment of climate impact studies in the region, including SWAT (Soil Water Assessment Tool) by Dile et al. (2013), Setegn et al. (2011), NFS (Nile Forecasting System) by Nawaz et al. (2010), Soliman et al. (2009), and HEC–HMS (Hydrologic Engineering Centre–Hydrological Modeling System) by Ebrahim et al. (2013). The influence of hydrologic model choice, however, is seldom investigated. Taye et al. (2011) utilize two conceptual hydrologic models to evaluate extremes in the Lake Tana basin: NAM (Nedbør-Afstrømnings-Model) and VHM approach (a Dutch abbreviation for lumped conceptual rainfall-runoff model). While they conclude that the uncertainty from the GCMs surpasses that of the hydrologic models, they highlight the need to further investigate uncertainty associated with different types of hydrologic models.

Communication of the various, propagating uncertainty sources is critical, however, most researchers opt for simply reporting ensemble mean results. The availability of the new Coupled Model Inter-Comparison Project Phase 5 (CMIP5) models provides an opportunity to utilize improved precipitation projections in the basin. In light of that, Jury (2015) conducts a statistical evaluation of CMIP5 model simulations, comparing modeled versus observed precipitation and maximum temperature over the Ethiopian highlands. The annual cycle, spatial distribution of mean and variance, and year-to-year fluctuations are considered in the evaluation. Based on their analysis, they select three models (HAD, CCSM, and GFDL) that

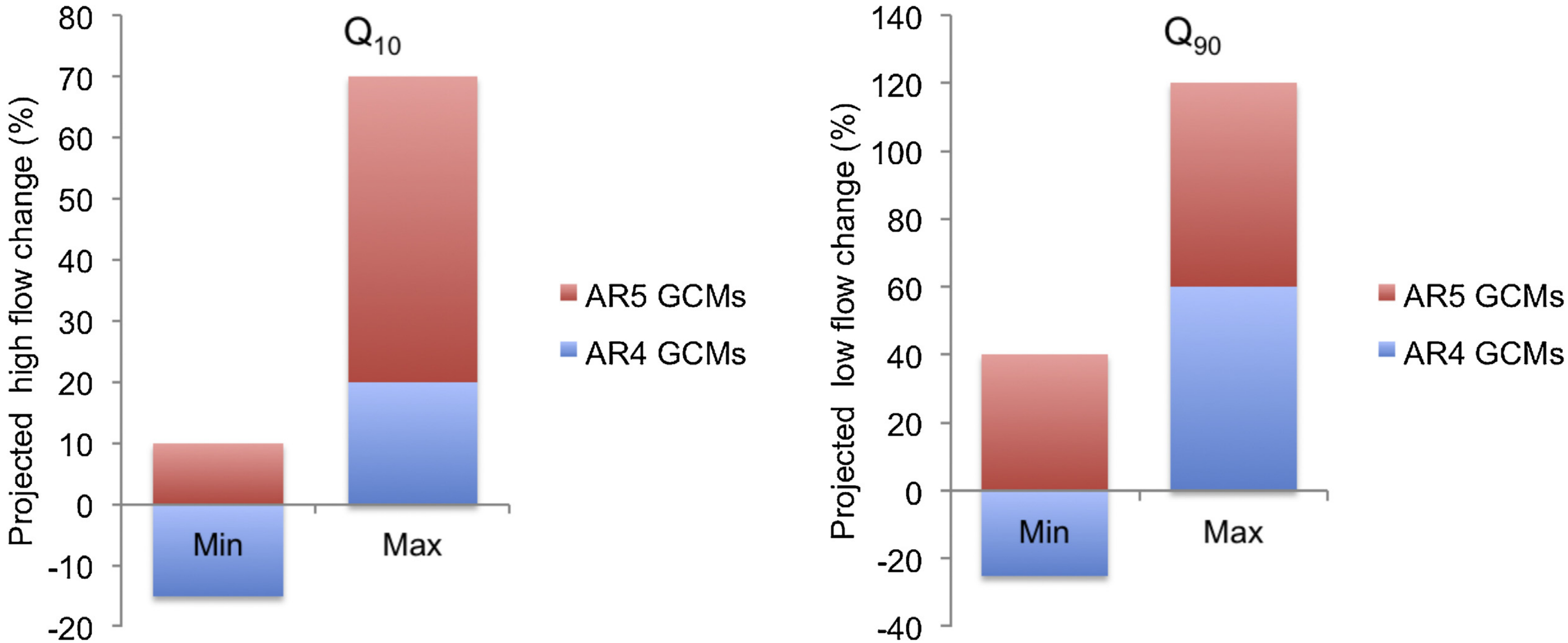

Fig. 5. Range of extreme streamflows projection for the 2050s based on results from two studies (Kim et al., 2008; Aich et al, 2014) for the upper Blue Nile basin using the previous (AR4) and new generation (AR5) of climate models.

are believed to perform superiorly across a number of metrics. They argue that an average of 'better' models may provide enhanced guidance to policy makers compared with the all-model ensemble. Another possibility is to test regional climate models with finer resolution if they provide better results for the region. Soliman et al. (2009) utilize a regional climate model (RegCM3) nested with ECHAM-5 GCM and found that the model well captured the climatology of the basin in terms of spatial and temporal pattern and seasonality of precipitation and temperature. This warrants more effort toward applying and evaluating regional climate models based on CMIP5 runs. With the availability of the Coordinated Regional Climate Downscaling Experiment in Africa (CORDEX Africa) outputs, this is within reach.

6. Conclusions

Hydrologic variability is one of the main challenges facing Ethiopia's water resources management. This leads to numerous research outputs exploring historical and future trends of precipitation and streamflow in the BNR basin. This review summarizes results from such studies and highlights that historical trends in the BNR basin have been predominantly stationary. We argue that multi-decadal oscillations appear to modulate the BNR high streamflow and the influence of changes in watershed characteristics is minimal. Failure to consider the influence of multi-decadal oscillations can lead to contradictory results in historical trend analysis. However, the temporal dynamics of low streamflow appears to be influenced by a combination of land and water management practices and changes in climate. Since the basin is reported to be undergoing substantial change in land use/cover, more emphasis on the impact of land use and water management changes is needed, particularly at the local scale. Moreover, further investigation and better understanding of the combined effects of land use/cover and climate change on streamflow across BNR basin is warranted.

This review highlights that while no two research studies in the BNR basin use a consistent number and type of climate models, emission scenarios, downscaling methods or hydrologic models, making comparisons challenging, most studies do agree on the wide range of expected precipitation and streamflow projections later in the 21st century. The consistent increasing temperature projections indicate that potential evapotranspiration may simultaneously increase and leads to reduction in streamflow. Although this needs further exploration given that potential evapotranspiration is a function of various meteorological variables. Effectively communicating these findings to end-users to foster knowledge transfer is non-trivial, but critical as they move toward adaptive planning under a changing hydrologic regime. Furthermore, it is equally important to recognize that factors such as population growth and land use change may play prominent roles in defining future trends.

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